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A REVIEW OF GAS TURBINE APPLICATIONS IN RENEWABLE-DOMINATED POWER SYSTEMS: CURRENT TRENDS AND FUTURE DIRECTIONS

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Abstract

Gas turbines play a pivotal role in renewable-dominated power systems, ensuring grid stability, flexibility, and efficient energy generation amid the challenges of variable renewable energy sources. This paper provides a comprehensive review of gas turbine applications, highlighting their integration with hybrid renewable systems, advancements in high-temperature materials, innovative cooling technologies, and fuel flexibility, including the shift toward hydrogen and biofuels. Key trends such as digitalized operations, predictive maintenance, and modular designs are examined, showcasing their potential to enhance operational reliability and efficiency. Challenges, including fuel supply variability, thermal stress from frequent startups, emission control requirements, and regulatory compliance, are analyzed. Additionally, opportunities for future research in next-generation turbine designs, alternative fuels, and decentralized power generation are discussed. By addressing these challenges and leveraging advancements, gas turbines are poised to remain critical enablers of grid reliability and sustainability in the global transition toward clean and renewable energy solutions.

Keywords: Gas Turbine, Power Generation, combined cycle, Heat Recovery Steam Generator (HRSG), fuel quality, renewable energy.

I. INTRODUCTION

Gas turbines have long been integral to energy generation, widely recognized for their efficiency, reliability, and versatility across industrial and aviation applications. As the global energy sector transitions toward renewable-dominated power systems, the role of gas turbines is undergoing significant transformation. These machines are increasingly being deployed to complement variable renewable energy (VRE) sources, such as wind and solar, by ensuring grid stability, reliability, and peak-load management[1].

Figure 1 depicts the mechanism of gas turbine engine.

1.1 Gas Turbine Engine

The performance of gas turbines in renewable-dominated systems heavily depends on the efficiency and reliability of critical gas-path components, including compressors and turbines. These components, however, are vulnerable to degradation caused by fouling, erosion, and thermal stress, leading to efficiency drops and mechanical failures. Advanced gas-path diagnostic technologies have emerged as vital tools for early fault detection and performance optimization, enabling predictive maintenance and minimizing operational disruptions[2].

Furthermore, the integration of gas turbines with renewable energy introduces unique challenges and opportunities. Technological advancements, such as hydrogen-fueled turbines, carbon capture systems, and hybrid configurations, are redefining the operational paradigms of gas turbines in these systems[3]. This review provides a comprehensive analysis of current trends and emerging directions for gas turbines in renewable-dominated power systems, addressing their evolving applications, technical innovations, and the critical challenges they face in achieving sustainable and efficient energy solutions[4].

1.2 Motivation of the Study

The transition to renewable energy has made gas turbines essential for addressing the variability of renewable sources due to their reliability, quick ramp-up times, and fuel adaptability. However, challenges like fuel flexibility, efficiency, and emissions control persist. This study explores the evolving role of gas turbines in renewable-dominated systems, highlighting trends and future directions to guide stakeholders in leveraging this technology for sustainable energy solutions.

1.3 Structure of the Paper

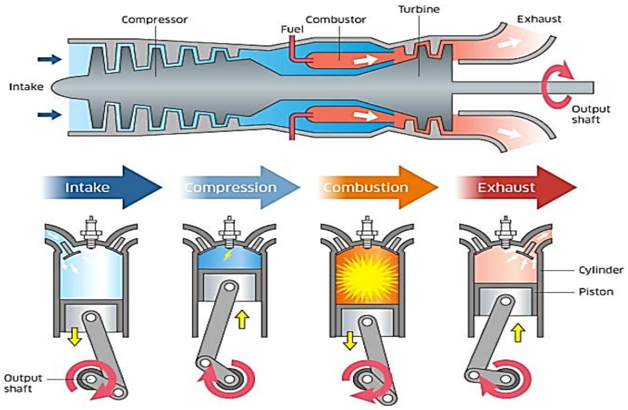
Here is the outline of the paper: An introduction to gas turbine technology is given in Section II. Section III explores their role in renewable-dominated systems. Section IV examines current and future trends in gas turbine applications. The literature review is located in Section V, and recommendations for further study are given in Section VI.

II. OVERVIEW OF GAS TURBINES TECHNOLOGY

Gas turbines are integral to modern power systems and industrial applications due to their efficiency, reliability, and adaptability. The chemical energy in fuel is converted into mechanical energy by these engines, which can subsequently generate electricity or power machinery. This section provides an overview of their principles, types, and critical components[5].

2.1 Principles of Gas Turbine Operation

Intake, compression, combustion, and exhaust are the four main stages of a gas turbine's operation as an internal combustion engine. Unlike reciprocating engines, it uses rotary motion. Compressed air is mixed with fuel in the combustor, where continuous combustion produces high-temperature, high-pressure gas[6]. This gas expands in the turbine, generating rotational energy to power the compressor and deliver energy through an output shaft. The fundamental workings of a gas turbine are displayed in Figure 2.



Basic principle of a gas turbine.

The four main steps of the Brayton cycle are what allow gas turbines to function:

- **Compression:** Compressors raise the pressure of the air by drawing it in from the surrounding environment. Essential for effective combustion, this procedure raises the air's density. In a standard compressor, the air pressure is increased step by step using a series of spinning and stationary blades[7].
- **Combustion:** The combustion chamber is responsible for igniting the mixture of fuel and high-pressure air. Because it transforms the fuel's chemical energy into thermal energy, this step is crucial. To avoid inefficient combustion and increased emissions caused by incomplete combustion, the ratio of fuel to compressed air must be carefully regulated[8].
- **Expansion:** The turbine part is responsible for expanding the high-temperature, high-pressure gases that are released from the combustion chamber. The expansion turns a shaft that produces mechanical work by driving the turbine blades. To power machinery like generators or propellers, the expansion process transforms thermal energy into mechanical energy[9].
- **Exhaust:** The exhaust system is responsible for releasing the exhaust gases once they leave

the turbine. The effectiveness of this step is dependent on the turbine's ability to transform the combustion process's energy into work. In order to maximise turbine efficiency, it is crucial to reduce energy losses and optimise exhaust flow[10].

Compressor and turbine efficiency, as well as the pressure ratio (a difference among an ambient pressure and a pressure at the discharge of the compressor), affect the gas turbine's performance. Another consideration is the temperature at the input of the turbine, which affects the efficiency of energy conversion [11].

2.2 Types of Gas Turbine: Impulse vs. Reaction

An apparatus that transforms the potential energy of a fluid into mechanical work that may be rotated is called a turbine [12]. A variety of turbines, such as steam, water, gas, etc., are available, each optimised for a certain input fluid. The two most common types of hydro-turbines are impulse turbines and reaction turbines, which are named after the ways in which the fluid (water) behaves.

- **Impulse Turbine**
  An impulse turbine is a specific kind of hydro-turbine that uses the kinetic energy of a water jet to turn the blades. An impulse turbine harnesses the power of flowing water to turn its potential energy into kinetic energy. The turbine is propelled by the speed of the water via a nozzle [13].

- **Reaction Turbine**
  A response turbine is a specific kind of hydro turbine that spins the runner by harnessing the pressure and velocity of the flowing water. As the water flows into the turbine casing and then out again as a result of the blades turning, here is where the response turbines are positioned in the stream [14].

Here is a Table I that outlines the main distinctions between impulse turbines and reaction turbines: Comparison between Impulse Turbine and Reaction Turbine in different methods

Basis of Difference	Impulse Turbine	Reaction Turbine
Definition	The water's kinetic energy, or impulse force, is used to spin the turbine.	The turbine spins by harnessing the potential energy of the water's kinetic and pressure forces.
Water Flow	Water flows through a nozzle and strikes the turbine blades.	The water flows over the turbine with the help of fixed guide blades.
Force on Blades	Rotates by impulsive force.	Rotates by reaction force on the blades.
Pressure of Water Over Blades	Pressure remains unchanged and equal to atmospheric pressure.	Pressure continuously decreases while flowing over the blades.
Decrease in Water Pressure	The nozzle is used to lower the	As the fluid passes over the blades,

	pressure before it enters the turbine.	the pressure drops.
Change in Pressure of Water	When the force of the impact hits the blades, all of the potential energy is transformed into motion.	No pressure change occurs before striking the blades.
Water Head	Suitable for large water heads.	Suitable for relatively low water heads.
Water Flow Rate	Suitable for low water flow rates.	Suitable for higher water flow rates.
Turbine Casing	Not necessary; casing prevents water splashing.	Necessary to seal from atmospheric pressure due to high inlet pressure.
Blade Profile	Symmetrical blade profile.	Asymmetrical, aerofoil-shaped blade profile.
Water Discharge	Proceeds straight to the tail race after leaving the turbine wheel.	Discharges into a draft tube before reaching the tail race.
Turbine Size	Smaller size for the same power output.	Larger size for the same power output.
Examples	Pelton wheel, Turgo turbine, Cross-flow turbine.	Francis turbine, Kaplan turbine.

2.3 Role of Gas Turbines in Renewable-Dominated Systems

The global energy landscape transitions to renewable-dominated systems, gas turbines play a critical role in ensuring grid reliability and stability[15]. They address the challenges of renewable energy intermittency, integrate seamlessly with hybrid systems, and contribute to load balancing, making them an indispensable component of modern energy infrastructure. Renewable energy hybridisation: an exhaustive analysis of integration tactics for environmentally friendly and cost-effective power production.

2.3.1 Addressing Renewable Energy Intermittency

Energy production by renewable resources, like wind and sun, is essentially intermittent, occurring only when outside circumstances are ideal [16]. Gas turbines provide a versatile and dependable answer to this problem by:

- Fast Ramp-Up Times: Gas turbines can quickly adjust their output to match fluctuations in renewable energy production, ensuring a steady supply of electricity[17].

- Backup Power Generation: During periods of low renewable energy output (e.g., cloudy days or calm winds), gas turbines can be activated to meet energy demands.

- Fuel Flexibility: A cleaner alternative to traditional backup power sources, modern gas turbines can run on a wide range of fuels such as biofuels, natural gas, and hydrogen [18].

- Their ability to provide on-demand power makes gas turbines a critical component of renewable-dominated grids, reducing the risk of blackouts and ensuring energy reliability.

2.3.2 Hybrid Systems: Gas Turbines with Wind and Solar

Gas turbines are increasingly integrated into hybrid energy systems that combine renewable sources like wind and solar. These systems leverage the complementary strengths of renewables and gas turbines:

Efficiency Gains:

- During periods of high renewable output, excess energy can be stored (e.g., in batteries) or utilised to produce hydrogen, which can later fuel gas turbines.
- Gas turbines can operate in combined cycle configurations, using waste heat for additional power generation[19].

Energy Storage Integration:

Hybrid systems with gas turbines can incorporate energy storage technologies, enabling stored renewable energy to be used during peak demand.

Examples of Hybrid Systems:

- Wind-gas Hybrid Systems: Wind turbines generate electricity, while gas turbines provide backup power during periods of low wind.
- Solar-Gas Hybrid Systems: Solar panels supply daytime energy, and gas turbines fill in the gaps during night or cloudy conditions[20].
- Power-generating systems benefit from these hybrid configurations in terms of efficiency, dependability, and sustainability.

2.3.3 Load Balancing and Grid Stability

This paper finds that controlling the grid stability is a major problem in renewables-intensive systems because of fluctuations in wind and solar energy [16]. Gas turbines contribute to:

- Frequency Regulation:

Normally, gas turbines can adapt equally well to changes in grid frequency; in those moments, it helps restore stability in the system due to variations in demand and supply[21].

- Voltage Control:

Gas turbines regulate voltage, hence ensuring that no power blackouts or equipment damages occur within the electrical network.

- Peak Load Management:

During emergence, a supply/demand dilemma, gas turbines are also used to cater for additional loads to guarantee a stable supply for the grid[22].

2.4 Support for Distributed Energy Resources (DERs):

Gas turbines can therefore be used in a strategic way to support DER and renewable generation where needed, to ensure localized grid stability.

These capabilities make gas turbines a key component of contemporary energy systems, where a transition to renewable energy sources does not affect the stability of power networks[23].

2.5 Challenges in Gas Turbine Integration with Renewable Systems

To guarantee effective and sustainable operation, there are a number of problems that must be solved when gas turbines are integrated into energy systems that are dominated by renewable sources. These challenges include fuel supply and flexibility, dynamics of operations in this hybrid systems and environmental/ regulatory compliance.

Fuel Supply and Flexibility

Gas turbines should be flexible enough to accommodate different fuels, biofuels, natural gas, and hydrogen in a bid to achieve the shift to the cleaner sources of energy. The coordinated realisation of fuel flexibility corresponds with the need to decrease carbon emissions and at the same time ensure secure energy supply [24]. However, this flexibility introduces challenges:

- Combustion Dynamics: There are disparities with regards to the combustion of fuels and how they influence the turbine and emissions. For example, hydrogen has significantly higher flame speed and combustion stability compared with natural gas, thus change in the design and operation of turbines etc[25].

- Infrastructure Requirements: Hydrogen as an off-gas is one of the other forms of fuel that can be adopted, but this entails huge investments in changing the present structures for storing, transporting and handling fuel.

- Supply Chain Reliability: Building a stable infrastructure of different types of fuels is difficult when setting up for a radical shift from fossil fuel types[26].

2.6 Operational Challenges in Hybrid Systems

Integrating gas turbines with renewable energy sources like wind and solar in hybrid systems introduces operational complexities:

- Load Following and Ramp Rates: Gas turbines need to follow changes of renewables which demand sophisticated control processes to address fluctuations.

- Thermal Cycling Stress: Fluctuating load demands can cause high thermal stress in the various components of gas turbines as a result of startups and shutdowns that are characteristic of renewable energy systems[27].

- System Integration: Managing these gas turbine systems and integrating the renewable energy sources and storage systems into the electricity generation loop requires complex energy management techniques[28].

2.7 Environmental and Regulatory Constraints

- Operating gas turbines within renewable-dominated systems requires compliance with stringent environmental regulations aimed at reducing emissions:
- Emission Standards: Gas turbines requires low NOx and CO2 emissions which can only be achieved through use of advanced combustion technologies and emission control systems [29].
- Carbon Pricing and Taxes: This means that economic policies, which put a cost on carbon emissions, can be of consequence to the function of gas turbines using fossil fuels [30].
- Permitting and Compliance: When it comes to installation and operation of gas turbines and introducing new fuels or technologies, there could be many legal barriers in the field [20].

III. CURRENT AND FUTURE TRENDS IN GAS TURBINE APPLICATIONS

The trends in gas turbine applications, both present and future, are highlighted in this section.

3.1 Current trends in gas turbine applications

Energy Efficiency and Emission Reduction:

Gas turbines have widely been incorporated in combined cycle power plants (CCPPs) owe to the fact that they arrange to make extra use of heat, which otherwise would be wasted. These systems can be as effective as 60-80%, hence preferred in terms of fuel saving and mitigation of greenhouse emissions. There are also solutions which concern the application of the progressive technologies of combustion to decrease the emissions of NOx and CO2, which is consistent with the sustainable development initiatives of the global ambience.

- Adoption of Natural Gas: Power generation using natural gases is gradually receiving attention over coal-firing stations because of the environmental impacts it will have. Natural gas is viewed as an inexpensive and freely available source of energy for power development due to its low emission profile compared to other fossil fuels. Thus, other policies that favour sustainable fuels fast-track their adoption even further.

- Integration with Renewable Energy Systems: The use of gas turbines is more pronounced in the enhancement of intermittency of renewable energy sources such as wind and solar through hybrid systems and microgrid applications. Being agile, startups and flexible they are indispensable for improving the stability of grids and enhancing energy security[31].

- Technological Advancements in Design and Materials: Innovations such as thermal barrier coatings (TBCs) and advanced alloys enhance the durability and efficiency of turbines. Improved cooling technologies like transpiration cooling allow turbines to operate at higher temperatures, increasing overall performance.

- Market Growth in Emerging Economies: The demand for sustainable power solutions, increased urbanisation, and industrialisation in the Asia-Pacific region are driving the enormous increase in gas turbine deployment, particularly in nations like Japan, China, and India. This region accounted for the largest market share in 2023 and is expected to grow further.

3.2 Future trends in gas turbine applications

The advancements in gas turbine technology have created opportunities for research aimed at improving performance, efficiency, and control systems. Below are key future trends and recommendations for further exploration:

Hydrogen and Alternative Fuels: Gas turbines are being adapted to operate on hydrogen and biofuels to support the global shift toward decarbonisation. Hydrogen-ready turbines are under development to achieve zero-carbon emissions[32], while biofuels provide an immediate lower-carbon alternative.

- Digitalization and Smart Operations: The integration of digital technologies, such as predictive maintenance systems, AI-driven performance optimisation, and real-time monitoring, is expected to revolutionise gas turbine operations[33]. These advancements will enhance reliability, reduce downtime, and improve overall efficiency.

- Focus on Decentralized Power Generation: Distributed generation systems, including microgrids and modular turbines, will play a key role in the future of energy. These systems offer localised power solutions, enhancing energy security and reducing transmission losses[34].

- Hybrid and Flexible Systems: Future gas turbines will integrate more seamlessly with energy storage systems and renewable sources, providing flexible solutions to manage grid demand and supply fluctuations. Innovations in turbine designs will focus on rapid ramp-up and ramp-down capabilities to support renewable energy integration[35].

- Advanced Cooling and High-Temperature Capabilities: Next-generation turbines will leverage improved cooling technologies and high-temperature materials to push efficiency limits further. These advancements will enable turbines to handle extreme operating conditions with greater durability and performance.

- Policy-Driven Growth: Stringent emission regulations and climate change initiatives will drive the adoption of cleaner gas turbine technologies. Incentives for low-carbon energy solutions will boost the deployment of turbines operating on natural gas, hydrogen, and other sustainable fuels[36].

- Focus on Modular and Lightweight Designs: The development of modular, lightweight turbines for industrial and mobile applications is expected to grow, addressing the needs of industries like aerospace, marine, and portable energy solutions.

IV. LITERATURE OF REVIEW

This section presents a literature review on Gas Turbine Applications in Renewable-Dominated Power Systems. A summary of the reviewed studies is provided in Table II for a concise overview.

In this study, Gospodinova, Dineff and Milanov (2020) goal of implementing a hybrid energy system in a single-family home is to demonstrate the degree to which emissions of greenhouse gases may be reduced. By combining solar and wind power with battery storage, this article suggests ways to cut down on dangerous emissions of CO2 and NO X. This article demonstrates that by combining renewable energy sources (solar and wind generators) with energy storage, the emissions of hazardous CO 2 and NO X may be reduced by around 50%[37].

In this study, Hadroug et al. (2019) give a presentation on the connections among control engineering models and how they are derived to meet specific requirements. The goal of this work is to present an optimisation method for modifying the speed and exhaust temperature of the gas turbine power plant under study using the PID, FL, and PSO controllers. The closed-loop system will then be able to adapt to changes in ambient temperature by reducing static error, rise time, response time, and maximum overshoot[38].

In this study, Haque and Bhuiya (2020) Discover the potential impact of combining effective load modelling with synthetic inertia on power system stability. The AIES is utilised for the purpose of testing the suggested hybrid model. Deregulation of the energy industry has occurred in Alberta. It is anticipated that power networks worldwide, including the AIES, would incorporate a greater amount of renewable energy. There may be temporary stability issues as a result of the increased penetration of renewable energy sources. A potential option for system stability is investigated in this research through the use of synthetic inertia and load modelling[39].

In this study, Sharma et al. (2017) primarily examine how various operational characteristics and environmental factors impact the efficiency of gas turbine power plants. They have also examined a number of research that used modelling and simulations. Studies using gas turbines equipped with heat exchangers, absorption chillers, evaporative coolers, and similar devices have also been evaluated. Future power generation may rely heavily on gas turbines to solve problems with efficient, environmentally friendly, and fuel-flexible power production. When it came time to generate electricity quickly and shut down on demand, gas turbines were often the go-to. The purpose of this article is to survey the literature on gas turbine power plants that has been published so far. Following a brief overview of the gas turbine's essential characteristics, they had included a chronological account of its evolution[40].

In this study, Shi et al. (2021) A comprehensive energy service is the end goal of an integrated energy station system that was developed by utilising resources from existing substations and building data centre stations, energy storage stations, 5 g base stations, photovoltaic power stations, gas turbine stations, etc., in order to facilitate the sharing of resources, which in turn supports the smart grid. The simulation results demonstrate robust performance and high penetration of renewable energy sources for the integrated energy station system that was constructed[41].

Presents a summary using previous studies based on Gas Turbine Applications in Renewable-Dominated Power Systems

Reference	Study Focus	Key Findings	Challenges	Limitations
[37]	Greenhouse gas emission reduction through hybrid energy systems in single-family houses.	Hybrid power supply system (solar and wind) with battery storage reduces CO2 and NOX emissions by approximately 50%.	Implementation at a broader scale for diverse households.	Limited to single-family houses; does not address cost implications of system deployment.
[38]	Optimisation of PID, FL, and PSO controllers for gas turbine power plant control.	Optimisation improves system adaptability to ambient temperature variations, reducing static error, rise time, response time, and maximum overshoot.	Ensuring optimisation parameters are adaptable to varying real-world conditions.	Focuses only on exhaust temperature and speed control; broader system efficiency is not addressed.
[39]	Stability in power systems with synthetic inertia and load modelling using Alberta's energy-only market.	Even as the use of renewable energy sources grows, synthetic inertia and load modelling help keep systems stable.	Transient stability challenges due to increasing renewable penetration.	Results specific to Alberta's power system; may not generalise to other deregulated energy markets.
[40]	Effects of operating parameters and atmospheric conditions on gas turbine power plant performance.	Gas turbines are efficient, clean, and flexible power generators suitable for fast start-up and shut-down applications.	Optimising performance under varying atmospheric conditions.	Reviews existing studies without experimental validation; focuses primarily on gas turbines.
[41]	Design and simulation of an integrated energy station system for resource sharing and renewable energy use.	Integrated energy station supports smart grids with high renewable energy penetration and resource integration.	Integration of diverse energy sources into existing systems.	Simulation-based results; practical implementation and cost analysis not explored.

V. CONCLUSION AND FUTURE WORK

Gas turbines are essential in renewable-dominated energy systems, ensuring grid stability, flexibility, and efficient power generation. Advancements in materials, fuel flexibility, and hybrid configurations have significantly enhanced their performance, enabling seamless integration with renewable sources. However, challenges like fuel supply, emissions, and operational complexities remain. Addressing these issues through innovation and policy support is vital for maximising their role in achieving a reliable and sustainable energy future. Additionally, ongoing research into hydrogen-based fuels and smarter operational technologies promises to further position gas turbines as a cornerstone of the global energy transition.

Future efforts should focus on developing hydrogen-ready turbines, integrating AI for performance optimisation, and advancing modular designs for localised energy solutions. Research into innovative cooling technologies and high-temperature materials will further enhance efficiency, while policy support will drive the adoption of cleaner turbine technologies.

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